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Cement and Concrete Composites 21 (1999) 39–48

Cement & Concrete Composites

Behaviour of composite soil reinforced with natural fibres

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Received 30 August 1996; accepted 15 July 1998

Abstract

Next to the food shortage, the housing shortage is one of the most crucial problems on earth. To improve this situation and make it possible to build more houses, particularly for low-income families, it is necessary to examine all locally available materials which can be used for construction. Bamboo, sisal and coconut fibres are materials which are available in abundance in Brazil and are not used in civil construction. To increase the amount of information concerning the physical and mechanical behaviour of these materials several research programmes were executed at Pontifical Universidade Católica in Rio de Janeiro (PUC-Rio) and Universidade Federal da Paraíba (UFPb) under the general supervision of the first author. In this paper new results are presented concerning the application of sisal and coconut fibres in conjunction with three types of locally appropriate soil for the production of composite soil blocks reinforced with sisal and coconut fibres. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Composite fabrication; Composite materials; Compression test; Failure; Fibre-reinforced soil; Natural fibres; Product development; Soil; Strains; Strength of material; Stress; Tensile test; Waterproofing

1. Introduction

Although the use of asbestos-fibre-reinforced cement boards is prohibited in many industrialized countries and the boards are considered as a hazardous material [1,2], they are used extensively in civil construction in Brazil. The main reasons for their popularity are strength, weight, durability and low cost. However, in tropical and subtropical regions, natural fibres from bamboo, coconut husk, sisal (agave), etc. are abundantly available and are relatively cheap. It is proven that vegetable fibres used with cement mortar can produce high-performance fibreboard, which can be used as a substitute for asbestos-cement. A higher economy can be achieved when vegetable fibres are used together with soil to form load-bearing structures [3–7].

In this paper further information [8] is given about the production of coconut and sisal fibres in Brazil. Data are presented concerning their physical and mechanical properties. Several investigations have been carried out on the physical and mechanical behaviour of coconut- and sisal-fibre-reinforced soil, which have shown very promising results. The presence of 4% of fibres, by weight, reduced the occurrence of visible cracks to null and gave high ductility soil blocks.

The constitutive relation of fibrous composite blocks made of three local soils mixed with sisal and coconut fibres will be discussed in a forthcoming paper. The main variables, which generally control the strength and performance of the developed composite, are tensile strength, the water absorption of the fibres and their bonding with soil. The influence of fibre/matrix ratio and water/soil ratio has been also studied in detail.

2. Production of sisal and coconut fibres

2.1. Coconut fibres

Coconut palms grow in tropical and subtropical regions between latitudes 20°N and 20°S. They are considered the most important palm trees in these regions. Besides timber, from coconut trees one can obtain food, oil, cosmetic products, animal food, etc. The transversal cross-section of a coconut fruit, which is egg shaped, consists of four basic parts:

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0958-9465/99/$ — see front matter
PII: S0958-9465(98)00033-X

- Epicarp, a shiny hard surface which partly prevents the loss of water from the fibres.
- Mesocarp, the thick fibrous part (interest of this work).
- Endocarp, the very rigid shell 5 mm thick for mature coconut fruit.
- Amendoa, the white edible part of the coconut fruit inside the large cavity, which contains coconut milk.

Mesocarp is the part from which fibres are extracted and, on the whole, in Brazil is considered as an agricultural residue. Except for a small number, which are used for the production of carpets, brushes and other handicrafts, the fibres are burned or dumped as rubbish. The largest coconut-producing countries in the world are the Philippines, Indonesia and India. In Brazil, according to the data given by the Brazilian Institute of Statistic and Geography (IBGE), 647451 tons/year are produced with an average production of 3339 kg per ha of which 95% of the production is situated in the north-eastern states of Brazil [9,10]. Non-organized production is not included here.

2.2. *Sisal fibres*

Sisal plantations were developed by the Mayas in Mexico before the arrival of Europeans. The name sisal originates from the port town Yucatan in Mexico and means cold water [7]. Large-scale production of sisal started in 1888 and thereafter its plantation has been propagated throughout tropical and subtropical regions. There are 57 species known to date [11,12]. Sisal fibres are extracted from the leaves of the plants, which vary in size, between 6–10 cm in width and 50–250 cm in length depending on the species, climate and soil in the plantation [12].

In general, Brazil, Indonesia and East African countries are the world's main producers of sisal fibres. The production of sisal in the main northeast states of Brazil, which are Bahia (BA), Paraiba (PB), Rio Grande do Norte (RN), Pernambuco (PE) and in Brazil as a whole, since 1983 is given in Table 1. It should be noted that the production of sisal in Brazil has reduced since 1985 and is creating serious local economic problems. Most of the sisal producers in these areas are looking for new ways to apply their product. It should be mentioned that the plantation of sisal has an ecological advantage as it has been proven to prevent desertification of the land.

3. Physical properties

To increase our knowledge about the sisal and coconut fibres new tests were carried out on fibres obtained from several sisal producers and from coconut fruits prepared in the laboratory of UFPb with the objective of producing a databank on these two important natural fibres. It is well known that the physical and mechanical properties of these fibres are affected by environmental changes, e.g. soil, time of harvesting, process of fibre separation, treatment, air humidity, temperature, etc. Therefore vast amounts of data need to be collected in order to proceed with a thorough statistical analysis.

Sisal fibres, according to the producers' classifications, are divided into three categories depending on their length as follows:

(a) short fibres with $L \leq 600$ mm;
(b) medium-sized fibres with $600 \text{ mm} < L \leq 700$ mm;
(c) long fibres with $L > 700$ mm.

There is no classification available for the coir fibres. After observation of many mesocarps it was concluded that the coconut fibres could be divided in two groups:

(a) short fibres with $L < 130$ mm;
(b) long fibres with $L > 130$ mm.

Table 1
Sisal production in Brazil and in its main north-eastern estates since 1985 (in tonnes)

Year	Paraíba		Bahia		Pernambuco		R.G. do Norte		Ceara		Brazil	
	Area	Production	Area	Production	Area	Production	Area	Production	Area	Production	Area	Production
1983	117816	88534	150000	75000	5265	4634	33240	12436	340	255	306661	180856
1984	110566	83341	170000	119000	5545	5767	33839	16140	310	511	320260	224763
1985	102221	78228	190000	190000	4343	4551	35821	17809	220	313	332605	290903
1986	94160	74671	190130	152186	1660	1488	35821	17910	220	163	322441	246418
1987	79610	64223	180000	108000	1653	1260	35011	17620	220	176	296494	191278
1988	82898	57522	182000	112840	1218	989	7151	8134	226	169	273495	189654
1989	72643	61628	182000	112840	1610	1426	8776	8006	228	171	265257	221233
1990	72643	61614	187500	150000	1800	1620	8776	8006	221	177	170940	221417

3.1. Length and diameter

To establish the length and diameter of the fibres under study 50 specimens for each group were chosen randomly. Their lengths were measured using a steel ruler, precision 0.5 mm, and their diameters, considered to be circular, were determined using a micrometer, precision 0.01 mm.

A summary of the results of measurements for minimum, maximum and average length and diameter of fibre is given in Table 2. It should be mentioned that the diameter of the fibres is averaged for all types of length as given in Table 2. In the available literature the variation in diameter is found to be between 0.05–0.5 mm and 0.1–0.60 mm for sisal and coconut fibres respectively [8,13].

3.2. Natural humidity, specific weight and water absorption

In order to find the natural humidity, fibres were at first air-dried for 5 days and then the same fibres were dried in an oven at 105°C for 24 h. Their weight was measured using electronic balance with a precision of 0.01 g. The natural humidity "H" then was calculated using equation 1.

$$H = \frac{P_d - P_o}{P_o} \times 100\% \quad (1)$$

Where P_d and P_o are the air-dried and oven dried weights of the fibres respectively.

The specific weight, γ, of the air-dried fibres was found using equation 2.

$$\gamma = \frac{P_d}{V} \quad (2)$$

Where V corresponds to the volume of the displaced water after immersion of fibres in drinking water after 24 hours. The calculated results for the minimum, maximum and average for all types of length are also given in Table 2. The results are based on 25 different measurements and are compatible with those given in the available literature. Their average specific weight for both fibres under study may be considered to be 9.4 kN/m^3.

3.3. Water absorption of the fibres

One of the main objectives of using fibres as reinforcing elements with soil matrices is to prevent cracking of the soil resulting from shrinkage. Tensile shrinkage cracks in the soil are mainly due to rapid and non-uniform drying. Reinforcing fibres in the soil matrices prevent cracking by adhesion or bonding to the soil. The main factors, which affect the adhesion between the reinforcing fibres and soil, are:

(a) cohesive properties of soil;
(b) the compression friction forces appearing on the surface of the reinforcing fibre due to shrinkage of the soil;
(c) the shear resistance of the soil, due to the surface form and roughness of the fibres.

The dimensional changes of natural fibres due to moisture and temperature variation influence all three adhesion characteristics. During mixting and drying of the soil, the fibres absorb water and expand. The swelling of the fibres pushes away the soil, at least at the micro-level. Then at the end of the drying process, the fibres lose the moisture and shrink back almost to their original dimensions leaving very fine voids around themselves. The swelling and shrinkage of a natural fibre in drying soil, as shown in Fig. 1, creates limitations in the use of natural fibres with soil matrices.

When establishing the adhesion properties of natural fibres with soil their rate of water absorption and dimensional change should be known. Subsequently, to improve the adhesion property, an effective water-repellent treatment in conjunction with soil must be found. The water absorption capacity of the naturally

Table 2
Length, diameter, natural humidity and specific weight of sisal and coconut fibre

Fibre	Classification	Length (mm)			Diameter (mm)			Natural humidity (%)			Specific weight (kN/m^3)		
		min.	max.	av.	min.	max.	av.	min.	max.	av.	min.	max.	av.
Sisal	Long	709	940	862	0.06	0.38	0.15	10.9	14.8	13.3	8.0	10.7	9.3
	Medium	610	700	661									
	Short	382	600	543									
Coconut	Long	132	266	186	0.13	0.56	0.27	11.4	15.8	13.7	7.7	10.8	9.5
	Short	67	130	105									
	1		2			3			4			5	

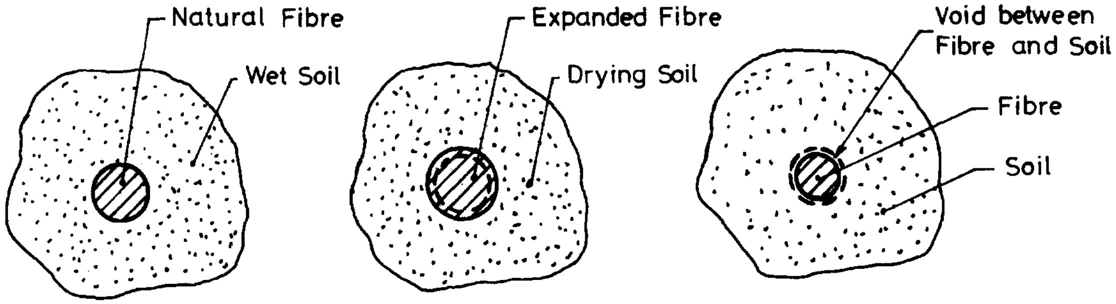

Fig. 1. Interaction of natural reinforcing fibre and drying soil.

dried fibres under study was established using equation 3.

$$W = \frac{P_h - P_d}{P_d} \tag{3}$$

in which P_d and P_h denote the weight of air-dried and soaked fibres in drinking water respectively. The measurements were carried out at 24 h intervals for 18 days. The average percentages of the water absorption for both sisal and coconut fibres are given in Fig. 2. It can be seen that the maximum water absorption of the fibres occurs during the first 24 h, especially for coconut fibres. However, sisal still absorbs a high percentage of water for up to 150 h. The new results show the same trend as observed previously [8].

The transversal and longitudinal changes in fibre dimensions during these predetermined periods also were measured and the results are given in [13]. An average increase of length and transversal section after 96 h was registered to be 0.84% and 12.9% for sisal, and 0.12% and 9.8% for coconut fibres, respectively. The results showed lower dimensional changes as compared to the first series of tests. This could be attributed to the process of preparing the fibres [8]. It can be seen that a significant increase occurs in the transversal section. This increase is higher for sisal fibres. In order to reduce water absorption of the fibres two different water-repellent agents, which are available locally, were studied.

4. Water repellent treatment

To produce an effective water-repellent treatment, thus improving the adhesion between natural fibres and soil, three main factors were considered:

1. The adhesive properties of the applied substance with fibre and soil.
2. The water-repellent property of substance.

The material had to be available locally at low cost.

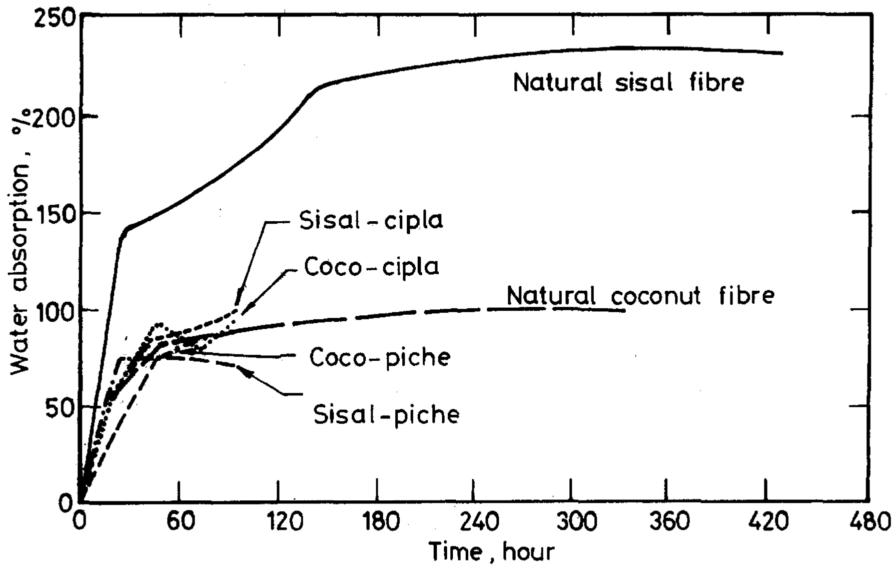

Fig. 2. Water absorption of natural and treated sisal and coconut fibres.

Bituminous materials such as "piche" and "cipla" are commonly used as a stabilizer and impermeabilization agent of soil in civil construction in Brazil, and were considered to satisfy all three conditions. Piche is a liquid bitumen and is made by Betumat in the state of Bahia. Cipla, also a liquid bitumen, and is made in Joinville, state of Paraná.

The percentage of water absorption of fibres treated with cipla and piche is given in Fig. 2. This is a mean value of 15 measurements. All the specimens were ≈100 mm long and were dried for several days before treatment. Then the fibre samples were immersed in the water-repellent product for several hours. The weight of the treated specimens was measured in the same manner as untreated fibres after immersing them completely in drinking water at room temperature. This procedure was repeated at defined intervals, for the determination of the moisture absorption.

It can be seen from Fig. 2 that piche is a more efficient method of impermeabilization. It should be noted that although the water absorption of natural sisal is much higher than that of coconut fibres, treated sisal shows almost reverse results. The water absorption of sisal treated with piche is 30% less than that of natural coconut fibres. This may be attributed to the microstructure of sisal fibres, which are more porous compared with coconut fibres. Therefore sisal fibres can absorb the water-repellent products more quickly than coconut fibres.

5. Mechanical properties of the fibres

Several factors, such as the method of testing, specimen length, soil condition, climate, time of harvest, process of fibre separation, storage condition, etc. influence the mechanical behaviour of the natural fibres. The influence of the first two factors is established in the laboratory and controlled with the objective of establishing a recommendation for a standard test. All the tensile tests in this work were carried out in a testing machine with the maximum capacity of 200 N (Branco-Marcallo, Varese). The load was applied at the rate of 0.1 mm/s (6 mm/min). In the previous work the influence of the specimen length was established. It was shown that the longer the specimen the lower the strength and strain [8].

The durability of the fibres when immersed in normal water was also studied. For this purpose 50 tests with the gauge length of 65 mm were executed on naturally dried fibres, soaked in drinking water and tested at 30-day intervals for up to 210 days. All the samples were dried before testing. The average values of the obtained results for long and short sisal and coconut fibres are presented in Fig. 3. In the strength–immersion time "S–t" diagram the value of the strain "ε"corresponding to the ultimate strain of the fibres are also given. It can be noted that the soaking time and lengths of the specimens do not strongly influence the ultimate strengths of the fibres.

These results confirm the superiority of sisal tensile strength as compared with coconut fibres, also, after long periods of immersion in normal water. The mean values of tensile strength of 580 MPa and 150 MPa for sisal and coconut fibres respectively are good estimates for design purposes. The strain values of 6 and 26% corresponding to the ultimate strength of the sisal and coconut fibres with their respective modulus of elasticity, E, of 18 and 3 GPa can be recommended based on the available results.

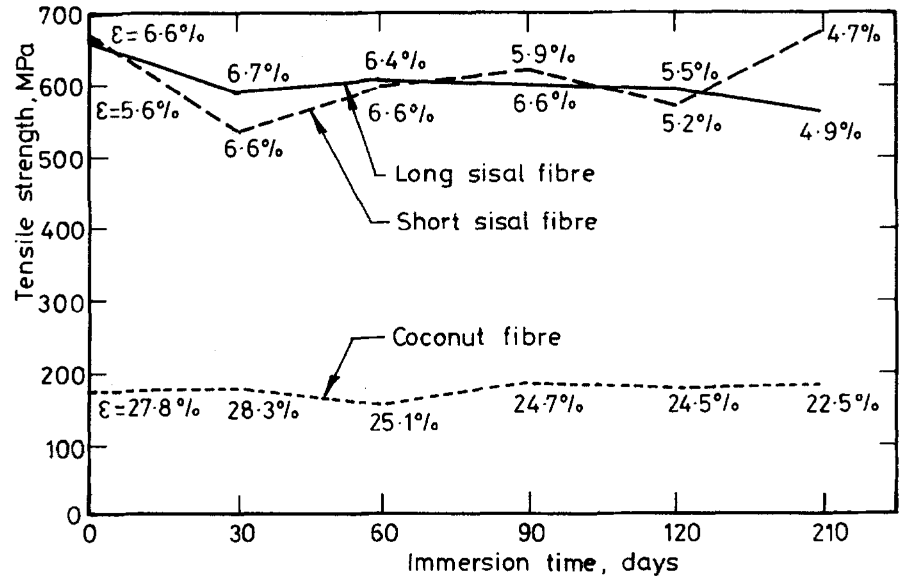

Fig. 3. Variation of tensile strength and strain of the fibres with time.

6. Properties of the soil

In the north-east of Brazil low-cost labour is abundantly available and soil is the cheapest constructional material. Therefore most houses are self-built using adobe blocks (puddled clay) or the traditional method of construction which is called locally "taipa" (pisé or rammed earth). These houses usually have a short lifetime of several years and present with large cracks after construction. Unfortunately, not much work has been done to study the properties of the local soil and consequently to find a skilful method for its use in the construction of sound and serviceable houses.

One of the main objectives of this work was to provide technical information concerning the soil commonly used in the more populated areas of Paraiba and recommend appropriate solutions to correct shortcomings of the soil in use. The soil samples were chosen from three regions, Taperoá, Areia and Campina Grande. First their particle-size distribution was established based on the sieve and sediment method according to the Brazilian code "ABNT" [14]. Then a series of tests was carried out to find the Atterberg limits consistency indices of the soils. These were: liquid limit "LL", plastic limit "LP", plasticity index "IP", shrinkage limit "LS" and the activity of the soils. Finally the compaction properties of the soil, which are shown in Fig. 4, were established.

The Taperoá soil has a granulometric particle size distribution very similar to the ideal Talbot curve and with IP of 6% and LL of 24% was found to be a stable soil when compared with the other two [8]. The Taperoá soil also showed a higher specific density which means that in general it has a higher compression resistance. Hence, further studies for the production of composite soil reinforced with fibres concentrated mainly on the Taporoá soil.

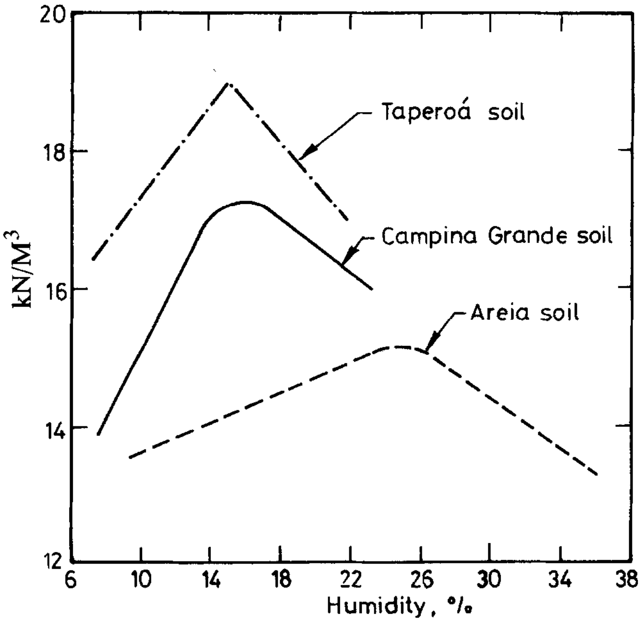

Fig. 4. Compaction properties of the studied soils.

7. Constitutive relation of the soil

Any soil is basically a mixture of mineral particles (solid), air and water, and is defined by parameters such as bulk density, dry density and moisture content. The soil under study has a maximum dry density of 18.8 kN/m^3 and moisture content of 14.5%. To manufacture adobe blocks the optimum water/soil (w/s) ratio was established. For this, the compression strength of the natural soil, considered as a reference sample, was calculated using cylindrical specimens 12 cm in diameter "D" and 10 cm in height "H". Test specimens were prepared by mixing soil with 17.5, 25, 28, 30 and 33%, by weight, of water in the mixer at a velocity of 1 Hz or until a uniform mixture was achieved.

The compression tests were carried out in a testing machine called Pavitest as shown in Fig. 5. The load was applied at a velocity of 0.1 mm/s. Soil deformation was measured by dial gauge at a precision of 0.01 mm. In each series five tests were carried out after 7 days of drying. The results are presented in Fig. 6, where the soil strength versus w/s is also included. It is observed that for this type of soil a w/s of 28% produces the highest strength and rigidity with good workability. A higher w/s ratio reduced the strength. This is expected as increasing the w/s ratio on drying means that more voids are present. Consequently the number of soil particles surrounding the embedded fibres is reduced, with a corresponding decrease in the effective interfacial contact area and debonding load.

It can be seen (Fig. 6) that the linear constitutive relation represents the behaviour of the soil under study. To find the specimens size effect a second series of tests was prepared on cylindrical specimens 8 cm in diameter "D" and 16 cm in height "H". This type of test is commonly used to find the mechanical property of soil. The new series of tests was carried out on soils with a w/s ratio of 28%. A comparison of the specimens size in Fig. 7 shows that the shorter the cylinder size the higher the values for the ultimate strength and the lower the rigidity on the stress–strain diagram.

7.1. Behaviour of soil fibre composite

Drying of the natural soil induces tensile shrinkage cracks mainly due to a non-uniform drying process in addition to its granulometric particle size distribution. To prevent cracking an optimum 4% of natural fibres

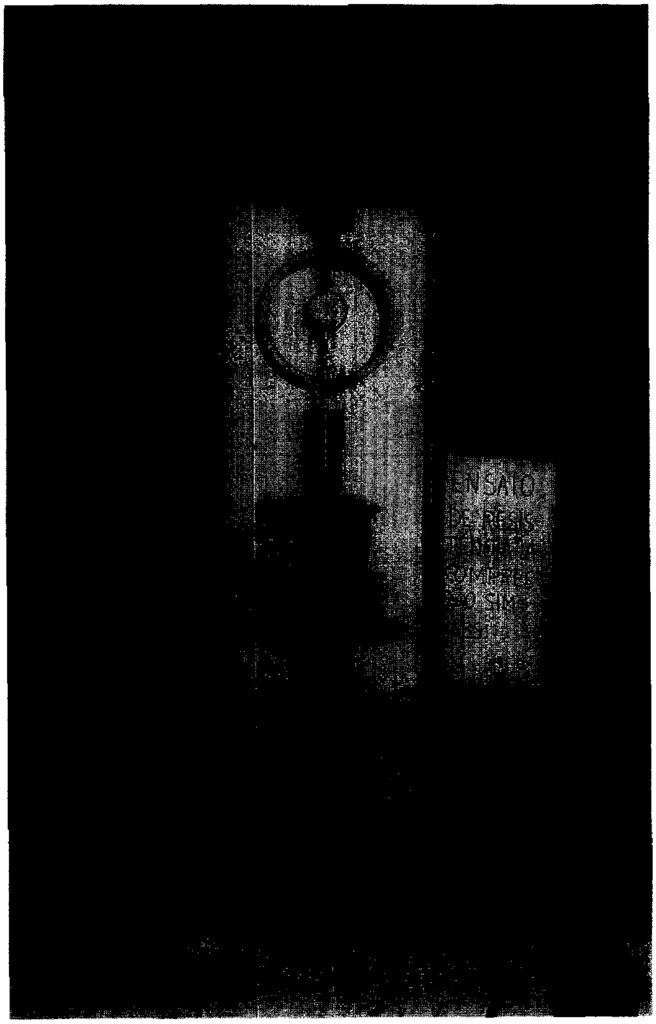
Fig. 5. Compression test of soil-fibre during application of load.

of 50 mm length in the Taperoá soil with two types of emulsified bitumen were used. Bituminous materials were used to waterproof the soil and fibres, thus increasing the impermeability and reducing the water absorption of the soil and fibres. In this manner the abrasive properties of the soil fibres composites were also improved.

The following test series was executed on composite material "CM". Six variables were considered. A designation system, which contained a complete description of the specimen, was used as follows:

1. Soil with a w/s of 28% and 4% sisal fibre denoted as CM28S4.
2. Soil with a w/s of 30% and 4% sisal fibre denoted as CM30S4.
3. Soil with a w/s of 28% and 4% coconut fibre denoted as CM28C4.
4. Soil with a w/s of 30% and 4% coconut fibre denoted as CM30C4.
5. Soil with a w/s of 28% and 4% sisal fibre and 2% emulsified bitumen denoted as CM28S4E2.
6. Soil with a w/s of 28% and 4% coconut fibre and 2% of emulsified bitumen denoted as CM28C4E2.

The influence of the drying period was also studied for 7, 28, 60 and 90 days, denoted as 7D, 28D, 60D and 90D. The identification system used explains all the variables studied. For example, the identification CM28C4E2D7 represents composite soil material with a w/s ratio of 28% using 4% sisal fibre in weight "S", (when coconut fibre "C") and, with 2% emulsion tested after 7 days.

Typical stress–strain curves for compression cylindrical specimens of 8 × 16 cm are shown in Fig. 8. Each curve represents the average result of five speci-

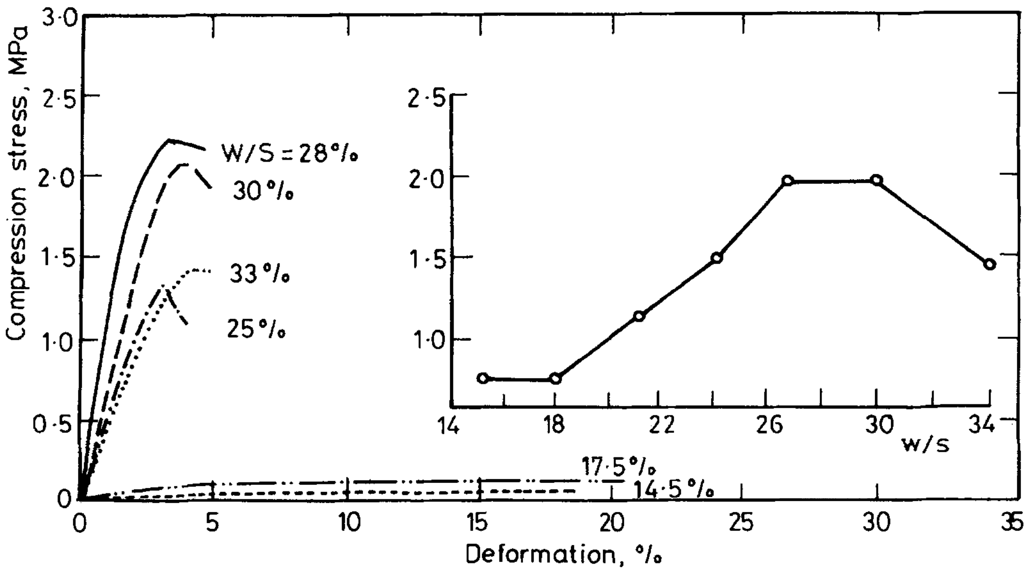

Fig. 6. Influence of the w/s on the constitutive relation of the soil.

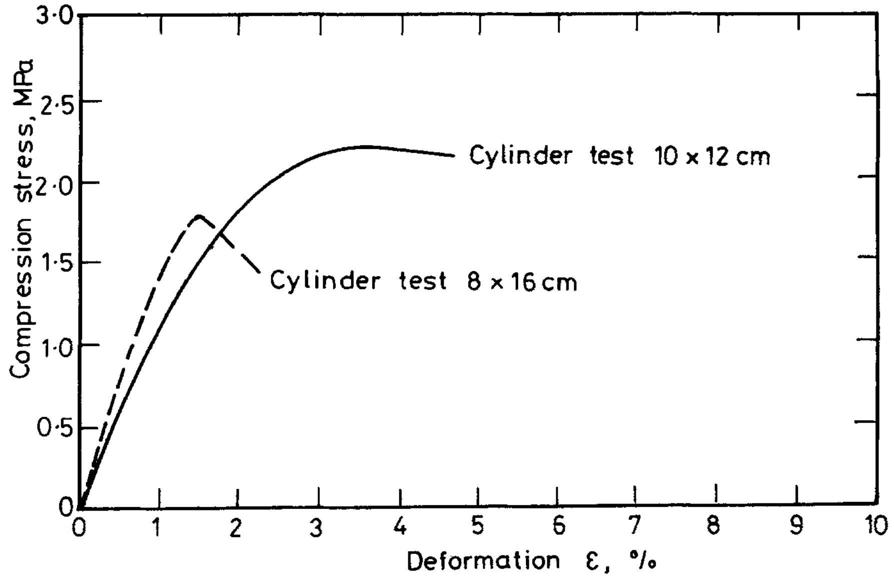

Fig. 7. Influence of the specimens size on the compression strength of the soil.

mens for the soil composite with a w/s ratio of 28%. To show the influence of fibre and/or fibre-emulsified bitumen, tests also were carried out on natural soil. These results are related to a soil matrix mixed with 4% sisal fibres and been tested after 7, 28, 60 and 90 days.

The failure mode of the specimen made of natural soil was very quick and almost without warning. In contrast, in the case of the composite material, after the ultimate load was reached the specimens still deformed and fine cracks could be seen on the surface of the specimens. This was the same for all the composite soil material. It can be observed in Fig. 8 that the stress–strain relationship is linear for all the test series up to maximum load. For the natural soil the final failure occurs immediately after the ultimate load. However, in tests on soil with 4% natural fibres work softening can be seen.

This may be explained by considering the redistribution of internal forces from the soil matrix to the reinforcing fibres. After final failure the soil-fibre composite was not disintegrated completely in contrast to natural soil specimens. Also it must be mentioned that the fibres hold together soil matrix and no rupture of fibres occurred although a loss of fibre bond was observed. The bonding between the soil and the sisal fibres will be examined at the microstructure level to establish the factors that influence soil-fibre bonds, in

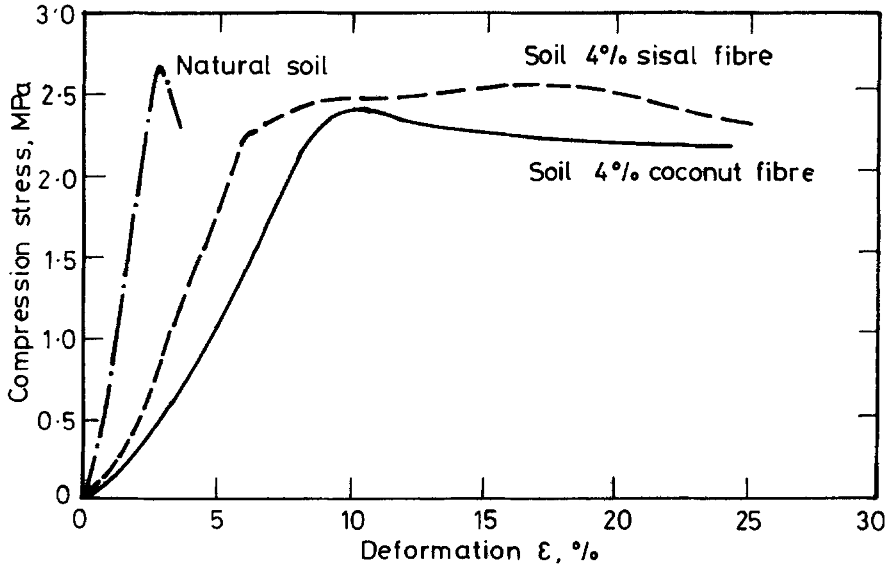

Fig. 8. Influence of 4% fibres on the stress–strain relationship of the soil.

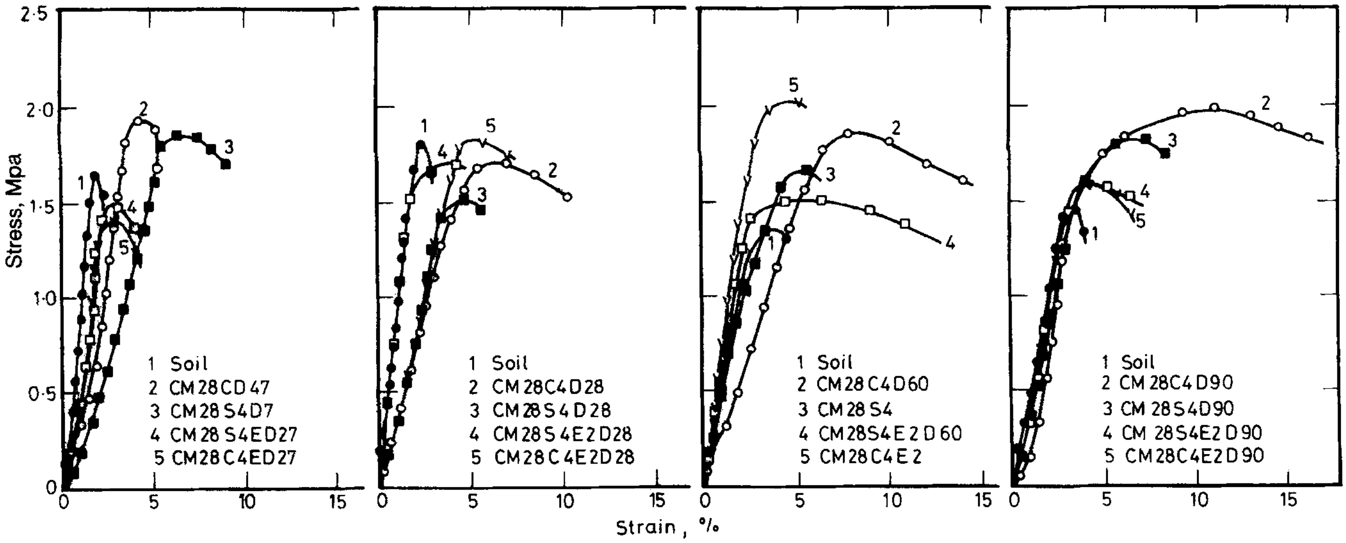

Fig. 9. Compression stress–strain relationship for test series after 7, 28, 60 and 90 days.

particular the penetration of clay particles into the fibres over time.

The compression stress–strain curves for the test series CM28S4E2 after 7, 28, 60 and 90 days are given in Fig. 9. On the same figure the test result for natural soil after 28 days is presented. It can be seen that debonding of fibres from the soil matrix takes place after reaching the maximum load and causes a decrease in load bearing. As mentioned earlier the optimum w/s ratio was established to be 28%.

Tests on the water absorption of the soil fibre–emulsion showed a significant reduction in the result. The results of these tests and those related to the production of the blocks and their durability will be presented in forthcoming papers.

8. Concluding remarks

Sisal and coconut fibres exist in abundance in Brazil. The feasibility of using these fibres in conjunction with a soil matrix to produce composite soil has been investigated experimentally. Test results have shown that for the Taperoá soil the optimum w/s ratio needed to produce a high-strength soil matrix is 28%. With this soil matrix inclusion of 4% sisal or coconut fibre imparted considerable ductility and also increased slightly its compression strength. The water absorption of sisal fibres is found to be much higher than for coconut fibres. The introduction of emulsified bitumen reduced the water absorption of the fibres under study significantly. However, introduction of the emulsion did not improve the bonding between the soil and fibres, but did improve significantly its durability.

One of the significant effects of the inclusion of natural fibres in the soil matrix was the prevention of shrinkage cracks due to the drying process. In this paper the 50 mm long fibres, introduced randomly, were used in the production of the soil composite. It will be necessary to investigate other dimensions in order to establish the optimum length for maximum strength. The effect of fibre orientation inside the matrix should also be studied. Furthermore, in order to understand better the bond between soil matrix and fibre, a study of the microstructure is needed.

Acknowledgements

The authors wish to express their appreciation to Ms Soenia Marques T. de Souza for her participation in the execution of the experiments. Appreciation is also to CNPq for the partial financial support of this project. Finally special thanks to Ursula Schüler-Ghavami, for the production of the drawings.

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